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A Method for Evaluating Transducer Loading Effects on Ultrasonic Transit Time Measurements

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ABSTRACT

Measurements of ultrasonic pulse velocities in specimens of structural materials offers a means of nondestructive stress analysis. An ultrasonic measurement technique and data processing scheme has been devised in which time intervals are measured between transducer resonance oscillations within the structure of successive unrectified echoes of an initial square-wave pulse rather than between echo leading edges. When the echo round trip transit times obtained using a series of transducers of different thicknesses are plotted against the transducer resonance periods, these time intervals determine a straight line. Actually, the data processing method yields several equally spaced values, one of which is the echo transit time while the others differ from it in steps of one cycle period of the resonant transducer vibrations which form the pulses. The result is a family of straight lines which have a single point in common at zero transducer resonance period. It is proposed that the transit time associated with this common point is the true travel time for sound in the medium unperturbed by transducer effects.

PROBLEM STATUS

This is an interim report on one phase of the problem. Work is continuing.

AUTHORIZATION

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A METHOD FOR EVALUATING
TRANSDUCER LOADING EFFECTS ON ULTRASONIC
TRANSIT TIME MEASUREMENTS

Recent investigations at this laboratory (1) have been concerned with the perturbing effect the presence of ultrasonic transducers may have on the measurement of transit time for sound in some structural materials. The original intention was to extend the information currently available regarding the effect of stress on the velocity of sound. It was readily apparent from this work that the bonding of transducers to the specimen under study introduced systematic errors much larger than the desired stress effects. This difficulty can be avoided in many instances by the data processing scheme described in this report. The need for an empirical method to define the unperturbed velocity from an ultrasonic measurement has been discussed some time ago by Eros and Reitz (2). A considerably different approach from the one to be described here has been recently presented by McSkimin (3).

The physical configuration of the experimental components is shown in Fig. 1 and is commonly termed a "through-ray" technique. Matched pairs (T and R) of quartz transducers are attached with Salol to opposite parallel faces of a specimen. One transducer (T) is used as a transmitter, which is excited by a square-wave electrical pulse, while the other (R) functions as a receiver. To make a determination for the transit time of sound in the medium, it suffices to measure the time interval between the excitation of the transmitter and the leading edge of the first wave packet to reach the receiver. Under favorable circumstances this time can be measured to within uncertainty of a few tenths of one percent (4). The present work will indicate that although experimental values for transit time can be established to this precision the true value or accuracy of measurement may nevertheless be several percent in error due to the transducer loading effect.

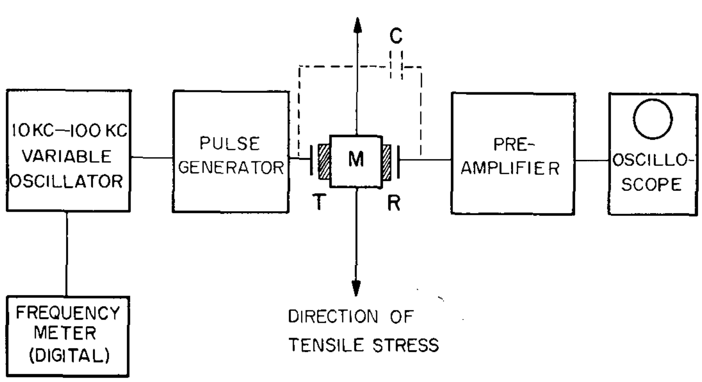


Fig. 1 - Instrumentation used to measure the ultrasonic transit time

The method to be described here does not depend upon a decision as to what constitutes the leading edge of the traversing energy packet. Instead, the principle of the method is to determine the time interval between arrivals of a characteristic feature, or cycle, within each echo of a train of echoes of the first excitation pulse. If this is done for several transducer thicknesses, and a constant time interval is obtained for each set, and if the specimen material is nondispersive, then these time intervals plotted against the reciprocal of the transducer resonance frequency (or vibration period) for each transducer pair will yield a linear plot. An extrapolation of this plot to intersect the ordinate axis at zero resonance period will yield a value for the transit time which corresponds to the hypothetical result obtainable with a massless transducer pair. It is proposed that this intercept value be considered the unperturbed transit time for sound in the specimen.

The essential components used in the experiment, together with a description of their function, are as follows. A variable frequency oscillator of high stability controls the pulse repetition rate of an adjustable-width square-wave pulse-generator over a frequency range from about 10 kc to 100 kc. This particular range is suitable for the 1/2-inch specimen thickness under consideration in this test. At the same time that this "dc" pulse shock-excites the piezoelectric transmitting transducer T, a small portion of this pulse signal is conveyed directly to the preamplifier input by means of the small capacitor C (Fig. 1) bypassing the ultrasonic elastic wave transformation sequence in the test specimen M. Capacitor C actually consists of a few inches of insulated wire attached to the ungrounded conductor from the pulse generator output and extends around the specimen in proximity to the input lead of the preamplifier but not in actual contact with it. The bypass pulse, adjusted in amplitude to be somewhat larger than the echo signal amplitude generated by the receiving transducer, serves to initiate the monitoring oscilloscope sweep. It also appears as a crude index in the field of view which the operator can move about at will superimposed upon the echo pattern.

The event sequences and their temporal relationships are illustrated in Fig. 2. The first part of the trace idealizes in miniature the "dc" step pulse applied to the transmitting transducer at time zero. The signal representation of the first ultrasonic wave packet, E_1^1, would be presented on the oscilloscope screen after time $\Delta t_1 + \Delta t_2$. These time increments represent the electronic travel time in the amplifiers and the travel time for the elastic wave to make one transit of the specimen respectively. Through capacitor C a reduced amplitude pulse is processed by conventional adjustable delay circuits before triggering the cathode-ray-tube sweep. It is thus possible to select a particular echo signal from trace 1 for presentation and enlargement on the oscilloscope screen. On trace 2, after a time lapse of $1/f_p$ seconds, another pulse is applied to the transmitting transducer, f_p being the pulse repetition frequency controlled by the variable frequency oscillator. Again this pulse initiates a series of ultrasonic waves into the specimen, and simultaneously a small replica of the pulse is conveyed to the preamplifier input. Since at this instant the oscilloscope screen is presenting the contours of say echo E_3^1, the pulse replica will also appear on the screen after an instrumental delay Δt_1, the same delay as for all signals transversing the amplifiers in cascade. This signal for the pulse replica will be added to that for echo E_3^1 and may appear something like the sample shown in Fig. 3. By adjusting the pulse repetition frequency the position of this index pulse in the trace can be moved along the trace at will. It is also clear from the comparison of consecutive pulse traces in Fig. 2 that the instrumental time delay Δt_1 appears in every sequence as an additive constant and hence cancels out as far as reading the true time, $1/f_p$, between pulses. The variable delay time, Δt_3, does not enter into the measurement of f_p either, since it is strictly concerned only with making a certain echo visible to the operator. The preamplifiers and oscilloscope circuitry serve merely as an aid to observing a desired coincidence and are not a part of the quantitative determination of elapsed time.

The way an observer deals with the index pulse and the various echo representations so as to extract a meaningful transit time to be used in velocity computations consists of measuring the time interval between component oscillations within the unrectified echo traces rather than the leading edges. The movable index is set on the maximum of a few consecutive component oscillations within each of a series of echo patterns, and the pulse repetition frequency is noted in each case.

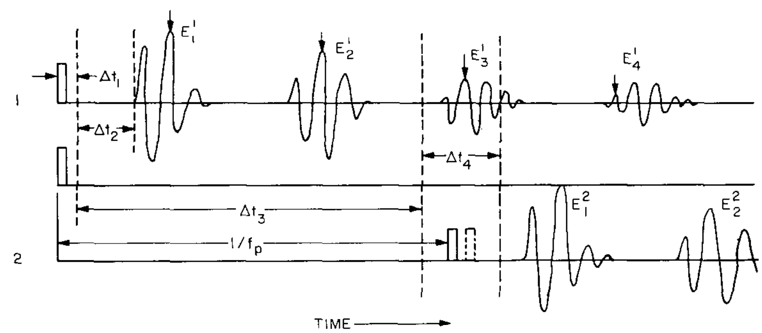


Fig. 2 - Time sequence of events between consecutive transmitter pulses. Trace 1 illustrates the excitation pulse beginning at zero time. This is followed by successive echoes caused by the first excitation pulse. The arrow points in wave packets E_1^1, E_2^1, E_3^1, and E_4^1 are corresponding points on the first arrival E_1^1 and successive echoes. Trace 2 shows the second excitation after a time $1/f_p$, where f_p is the pulse repetition frequency. ΔT_1, ΔT_2, ΔT_3, and ΔT_4 are respectively the time delay in the amplifiers, one transit travel time, the sweep trigger delay (variable), and the controllable sweep duration.

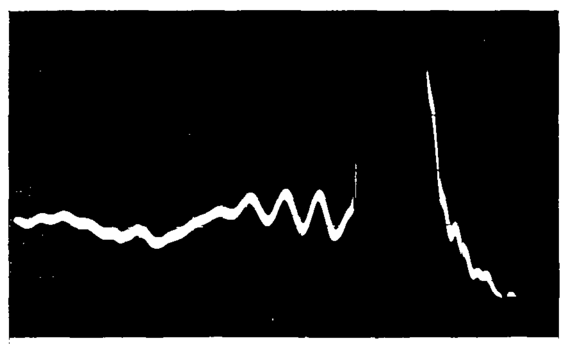


Fig. 3 - Transmitter pulse superimposed on an echo trace belonging to a previous pulse excitation

A typical set of values for the reciprocals of the pulse repetition frequencies is displayed in Table 1. The values for the cycle tagged in consecutive echos are matched so that the time differences between columns and along the same row are constant. This is not a single-valued process and as shown in Table 1 equally valid constant differences could be obtained along the indicated diagonals. These matching sequences yield time intervals which differ by one cycle period of the resonant transducer vibration. While this period is a constant for a given transducer thickness, the computed time interval between echoes is multivalued. At first this ambiguity might appear to render the scheme useless, but in fact it serves a valuable function in the graphical extrapolation as will be shown.

For each transducer thickness chosen it is possible to acquire an array similar to Table 1 but with a different value for the resonance period and another set of round trip transit times. These are now plotted as in Figs. 4 and 5 using the resonance period as the abscissa for the multivalued round trip transit times belonging to each transducer pair. A family of lines can be drawn through these points and through a common intersection on the ordinate axis. This is what one should expect if the medium is nondispersive

Table 1
Elapsed Time (μsec) Between Transmitted Pulse and Component Echo Cycles for HY-80 Steel Sample

Echo No.	2	3	4	5	6	7	8	9	10	11	12	13	14
Times	11.1528	15.4877	19.7939		A								
for consecutive	10.9844	15.3162	19.6137	23.9502	28.2532	32.5737							
cycles	10.8382	15.1540	19.4814	23.7885	28.1027	32.4194	36.7251				C		
in each	B	15.0307	19.3381	23.6497	27.9602	32.2692	36.5686	40.9029	45.2183	49.5250	53.8459	B	
echo				23.5266	27.8280	32.1361	36.4653	40.7635	45.0687	49.3810	53.6932	58.0248	62.3429
					27.7330	32.0355	36.3258	40.6442	44.9490	49.2635	53.5753	57.8844	62.1871
								40.5429	44.8535	49.1465	53.4536	57.7626	62.0751
							C			49.0198		57.6441	61.9482
													A

Average Interval Between Echoes

Parallel to	Time, (μsec)	Transducer resonance period, (μsec)
A-A	4.179	
		0.132
B-B	4.311	
		0.133
C-C	4.444	

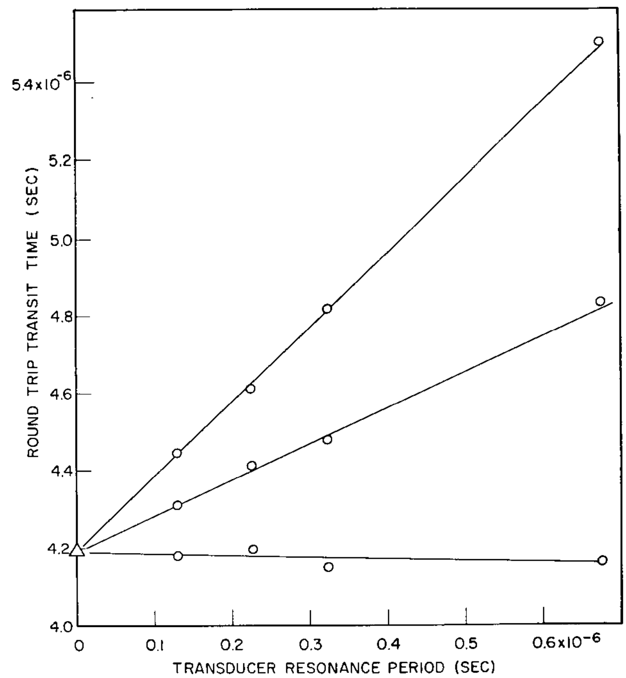
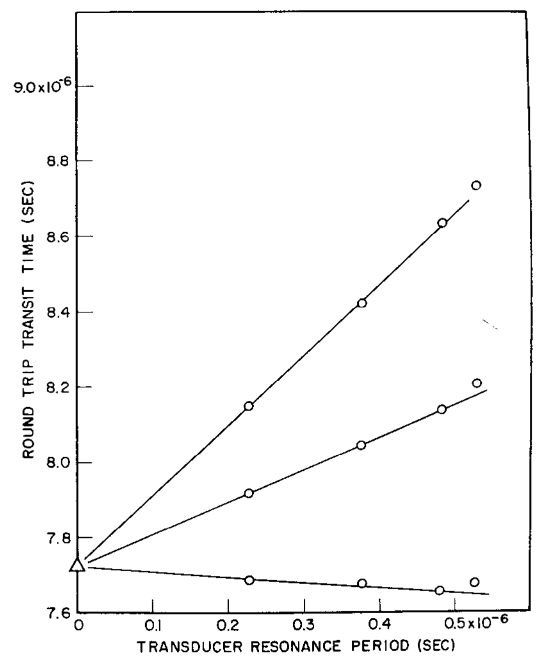


Fig. 4 - Round trip transit time for longitudinal mode ultrasonic waves in a specimen of HY-80 steel (density 7.8, thickness 1.235 cm) as a function of transducer resonance period

Fig. 5 - Round trip transit time for shear mode ultrasonic waves in a specimen of HY-80 steel (density 7.8, thickness 1.235 cm) as a function of transducer resonance period



and if the transducer vibration period could be reduced to zero by selecting thinner and thinner plates. Thus the intercept value represents an unperturbed transit time, obtained with a massless transducer and is single valued.

This graphical sequence can be phrased in a slightly different way by going back to Fig. 2, which depicted the process of tagging consecutive cycles in the echo pattern. If the separation between cycle maxima is allowed to diminish indefinitely (which means the resonance frequency approaches infinity) it matters little which cycles are identified in consecutive echo patterns since their separation is indefinitely small. The echo wave packet becomes so narrow that no internal structure is resolvable and the echo separations are the true transit time. This state of affairs is experimentally unattainable, but the extrapolation to the common intercept point for the family of lines in Figs. 4 and 5 approximates this situation to a practical degree.

Conventional transit time measurements made on the leading edge portion of the first few well-defined echoes yield results which tend to fall along the central branch in each case shown. The velocities computed from such data are significantly lower than those derived from the extrapolated intercept transit time. Longitudinal mode data for tungsten, titanium, silica, and magnesium have been included, Figs. 6, 7, 8, and 9 respectively, to show that the tendency to overestimate the transit time increases as the density of the specimen decreases. There will also be a tendency to overestimate the transit time if the data are plotted as a function of uncorrected transducer thickness. The uncorrected thickness parameter does not take into account the compliance of the specimen, whereas the resonance period does. For example, the zero thickness intercept occurs along the dashed vertical line in Figs. 8 and 9. Thus the value suggested in Ref. 1 for silica should be adjusted still lower (from 6.74 to 6.53 microseconds per round trip) if the data processing scheme described above is accepted as a criterion.

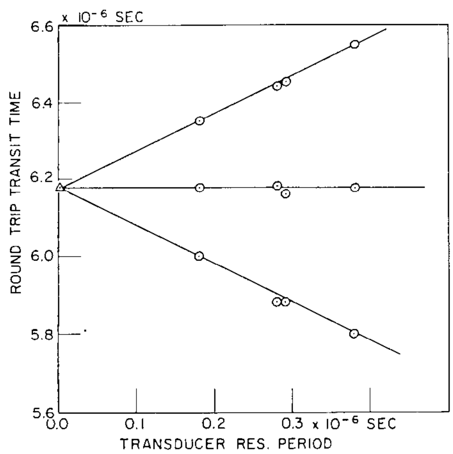


Fig. 6 - Round trip transit time for longitudinal mode ultrasonic waves in a tungsten specimen made of sintered pellets (density 19, thickness 1.606 cm) as a function of transducer resonance period

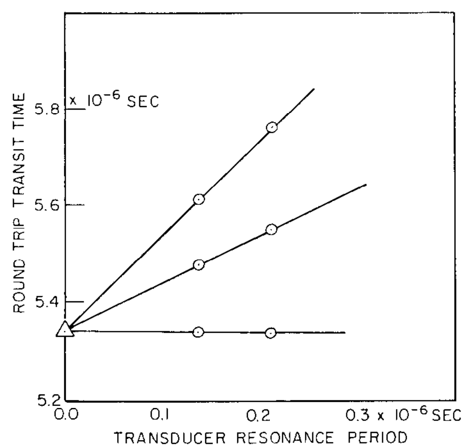


Fig. 7 - Round trip transit time for longitudinal mode ultrasonic waves in a titanium specimen (density 4.4, thickness 1.656 cm) as a function of transducer resonance period

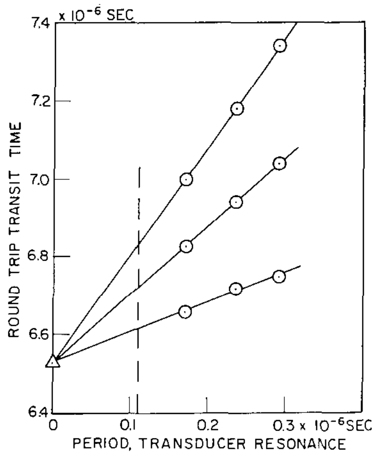


Fig. 8 - Round trip transit time for longitudinal mode ultrasonic waves in a clear silica specimen (density 2.2, thickness 2.010 cm) as a function of transducer resonance period. This is the same specimen used in Ref. 1.

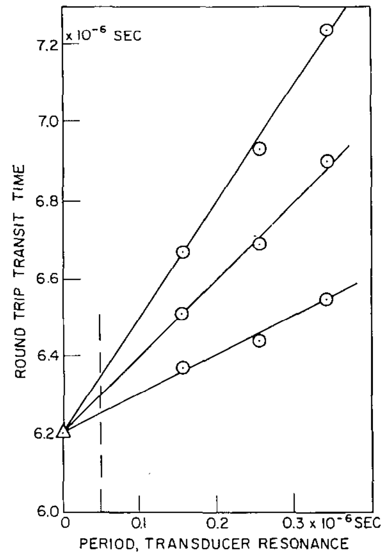


Fig. 9 - Round trip transit time for longitudinal mode ultrasonic waves in a magnesium specimen (density 1.7, thickness 1.833 cm) as a function of transducer resonance period

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